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Solar Energetic ^{3}He Mean Free Paths: Comparison Between Wave-Particle and Particle Anisotropy Results

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Abstract. Energetic ^{3}He particle mean free paths are calculated using in-situ wave amplitudes. The wave polarization (outward propagating, arc-polarized, spherical) and wave **k** directions (outward hemispherical) are included in a first-order cyclotron resonant calculation. Values for λ_{W-P} are ~ 0.2 AU. This is roughly ~ 5 times smaller than the particle mean free path as determined from modeling applied to measured front-to-back ^{3}He particle anisotropies. It is suggested that this difference is due to much slower pitch angle diffusion through 90°.

INTRODUCTION

In the past, particle transport from the solar corona to 1 AU has been studied by inferring the amount of pitch angle scattering that has taken place from an analysis of the particle distributions themselves, or by taking a characteristic interplanetary wave spectrum and theoretically calculating the amount of scattering that should have taken place assuming that the spectrum is representative (1, 2, 3). For a detailed discussion of the two methods, see (4) and (5). Calculation of the energetic particle scattering mean free paths using the magnetic field data and a quasi-linear theory of the field fluctuations has led to a long-standing discrepancy wherein this calculated mean free path is generally much smaller than the mean free paths derived from particle measurements. Some recent theoretical studies (6, 7) have obtained improved results (i.e., larger calculated particle scattering mean free paths) by using more complex models for the waves. Wanner et al. (8) presented evidence showing that the "slab" turbulence approximation was fundamentally flawed, and this was followed by Bieber et al. (9), who showed that two-dimensional (2D) turbulence was playing a major role. Bieber et al. (9) applied a 2D model to ~ 10 MeV proton observations from *Helios*, and found good agreement between the mean free paths calculated from the turbulence and from the energetic particle observations.

It is known that the amount of wave power present in the interplanetary medium can vary by orders of magnitude (10). It is the purpose of this paper to examine the simultaneous 1 AU LF wave properties (at frequencies near the particle cyclotron resonance) during ^{3}He rich events taken from (11). These solar energetic particles have energies near 1 MeV/nucleon, much lower than the $\sim 10-20$ MeV energies considered in recent studies (5, 9). These results will be compared to the mean free paths for the same events as determined from modeling applied to the measured 1 AU particle anisotropies.

RESULTS

^{3}He-Rich Events

Figure 1 shows the May 17, 1979 energetic ion event. Three He energy channels are given in the top panel. Velocity dispersion is clearly present, with the highest energy particles arriving first, as expected for propagation from a remote source. The magnetic field is given in the next four panels. The field is relatively quiet during the particle onset. The fluctuations in the three components are small, and the field magnitude is $\sim 3-5$ nT. An examination of the solar wind velocity (bottom panel) indicates that this particle event occurred in the far trailing part of a high velocity stream. This general region is noted for a lack of large amplitude Alfvén waves (12).

To quantify the characteristics of the interplanetary fluctuations present during this particle event, we have made power spectra of the magnetic field components and the magnitude. We have used a field-aligned coordinate system to determine the power due to transverse fluctuations and the power due to compressional variations. The transverse wave power is responsible for resonant pitch angle scattering and is the important quantity for the calculations presented in this paper.

The transverse power spectra for the nine (11) particle events have been calculated and compared with power spectra for "quiet", "intermediate" and "active" periods (from (13)). It is found that the interplanetary medium is typically "quiet" during the ^{3}He-rich events.

A proper description of interplanetary Alfvén waves is that they are phase-steepened, arc-polarized spherical waves (10). For purposes of the calculations here, we can assume that they can be approximated as linearly polarized waves with equal power present in right- and left-hand rotations.

The **k** direction of rotational discontinuities, the phase-steepened edges of interplanetary Alfvén waves has been shown to be isotropic (14, Fig. 15). Since Alfvén waves are outwardly propagating (14, Fig. 6), the wave **k** distribution is an outward hemisphere.

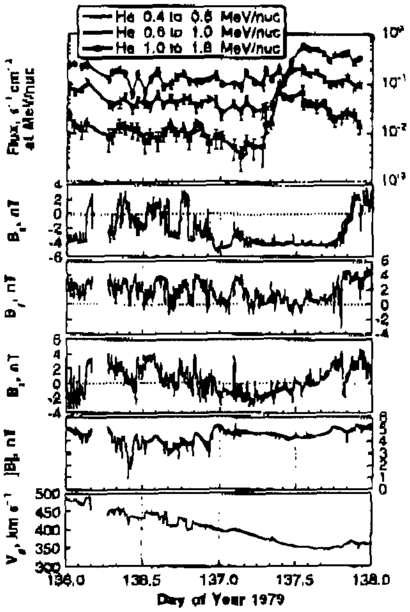

FIGURE 1. Particle flux, magnetic field and solar wind velocity for 16-17 May, 1979.

Scattering Mean Free Paths Determined by Particle Measurements

The scattering mean free paths for the nine ^{3}He events were obtained by comparing the event time/intensity profiles and anisotropies with the predictions of a Boltzmann equation model of interplanetary scattering which includes the effects of particle pitch-angle scattering and adiabatic defocusing as the particles move through magnetic fields of varying strength (15, 16, 17). Mason et al. (3) published numerical solutions of this equation based on the technique of (18) for observations from the *ISEE-3* ULEWAT instrument for nominal values of solar wind speed. We use these solutions here to estimate the scattering mean free paths. The results are given in Table 1.

Resonant Wave-Particle Interaction Calculation of Mean Free Paths Using IMF Power Spectra

The particle pitch angle diffusion coefficient (i.e., pitch angle scattering rate) has been derived in (19) and (20). The condition of first order cyclotron resonance between the waves and the anti-sunward directed particles can be written as:

$$\omega - k_{||}V_{||} = -\Omega \tag{1}$$

In the above, ω and **k** are the wave frequency and wave vector, Ω is the particle cyclotron frequency in the ambient magnetic field. The particle velocity **V** has a parallel component $V_{||} = \mu V_0$, where μ is the cosine of the particle pitch angle.

For Alfvén waves propagating in the solar wind plasma frame, the phase velocity is V_A. Taking the angle between **k** and B_0 to be θ and the angle between **k** and $\mathbf{V}_{SW}$ to be ψ, Equation 1 now becomes:

$$2\pi f\left(1 - \frac{\mu V_0}{V_{SW}\cos\psi}\cos\theta\right) = -\Omega \tag{2}$$

If the particles of interest are He^{++} and of 0.4 MeV/nucleon energy, $V_0 = 8.8 \times 10^8$ cm/s is much larger than the solar wind speed, V_{SW}. The ions are resonant with right-hand polarized waves, therefore in the final estimate of mean free paths, the effective wave transverse power should be $(P_1 + P_2)/2$, where 1 and 2 indicate two transverse directions to the ambient field.

Following equation (3.9) of (19), the pitch angle scattering rate for a given resonant velocity due to interactions with waves in a wave-number band of width Δk about resonance is:

$$D = \frac{(\Omega^{++})^2}{2\pi}\left(\frac{V_{SW}\cos\psi}{\mu V_0 \cos\theta}\right)\frac{P_{res}}{B_0}, \quad P_{res} = \left.\frac{(B')^2}{\Delta f}\right|_{res},$$
$$\Delta f = \frac{1}{2\pi}\Delta k V_{SW}\cos\psi \tag{3}$$

Table 1. Mean Free Paths for 1 MeV/nucleon ^{3}He-rich "Scatter-free" Events

Event (Date)	B_0 (nT)	$\Omega_{^3He_{++}}$	$P_{transverse}$ (nT^2/Hz)	Scattering Rate (s^{-1})	λ_{W-P} (AU)	λ_{He} (AU)
23 Oct 1978	6.30	0.402	$3.26 \times 10^{-3} f^{-1.7}$	9.36×10^{-4}	0.10	1.0
26 Dec 1978	8.11	0.517	$2.81 \times 10^{-3} f^{-1.7}$	5.25×10^{-4}	0.18	1.0
17 May 1979	4.63	0.293	$6.58 \times 10^{-4} f^{-1.8}$	5.50×10^{-4}	0.17	0.5
14 Dec 1979	9.93	0.634	$7.43 \times 10^{-3} f^{-1.7}$	9.84×10^{-4}	0.09	2.0
13 Jan 1980	6.25	0.399	$1.89 \times 10^{-3} f^{-1.7}$	5.50×10^{-4}	0.17	0.5
9 Nov 1980	11.47	0.732	$4.82 \times 10^{-3} f^{-1.7}$	4.99×10^{-4}	0.19	0.3
14 Nov 1980	7.41	0.473	$4.91 \times 10^{-3} f^{-1.8}$	1.76×10^{-3}	0.05	0.5
31 Jul 1981	9.66	0.616	$3.60 \times 10^{-3} f^{-1.6}$	3.14×10^{-4}	0.30	0.5
12 Feb 1982	15.56	0.993	$1.08 \times 10^{-2} f^{-1.7}$	6.66×10^{-4}	0.14	0.5

Increase by factor of 1.1

divide all numbers by 1.1

where B' is the wave amplitude in resonance with the particle. Assuming the wave power spectra to have a power spectral index of α, that is, $P_{res} = A f_{res}^{-\alpha}$ and $\mu V_0 \cos\theta \gg V_{SW}$, the effect of averaging over the θ angle~~s~~ and ψ (at 1 AU) is:

$$
\begin{aligned}
\langle D\rangle_\theta &\cong \frac{1.1}{\alpha} D|_{\theta=0} \\
&= \frac{(\Omega^{++})^2}{2\pi}\frac{1.1}{B_0^2}\frac{1}{\alpha}A(f^{++})^{-\alpha}\left(\frac{\mu V_0}{V_{SW}\cancel{\cos\psi}}\right)^{\alpha-1} \qquad (4)
\end{aligned}
$$

Averaging over the cosine of the particle pitch angle gives:

$$
\langle D\rangle_{\theta,\mu} = \frac{1.1}{\alpha^2}\frac{(\Omega^{++})^2}{2\pi}\frac{V_{SW}\cancel{\cos\psi}}{V_0}\frac{1}{B_0^2}A\left(\frac{V_{SW}\cancel{\cos\psi}f^{++}}{V_0}\right)^{-\alpha} \qquad (5)
$$

The time for scattering one radian in pitch angle T is $\sim 1/D$, and the particle mean free path is: $\lambda_{W-P} = TV_{He}$, where λ_{W-P} stands for wave-particle interaction estimate of the mean free path.

In this paper, we have considered only the first order cyclotron resonance term ($n = -1$). Use of higher order cyclotron resonance terms is more theoretically complete, but should only change the results slightly.

The results of the calculations are shown in Table 1. λ_{W-P} ranges between 0.05 and 0.30 AU while λ_{He} ranges between 0.3 and 2.0 AU.

DISCUSSION

Although the wave polarization, wave normal distributions, and in-situ transverse power spectra were included in this study, there are still substantial differences between the calculated λ_{W-P} and λ_{He} values. Previous works (21) have noted even greater discrepancies between the two values.

We note that $\langle D\rangle_{\theta,\mu}$, the average diffusion rate, is the typical quantity calculated. The value $1/\langle D\rangle_{\theta,\mu}$ and the particle velocity are used to derive λ_{W-P}. However, λ_{He} is the mean free path derived from particle pitch angle scattering across 90° pitch (where $D = 1/\tau = 0$). The time τ to diffuse across 90° pitch from quasilinear theory is infinite. Could this be the primary difference between the λ_{W-P} and λ_{He} values?

To examine this further, we perform a test particle simulation, in which ion orbits are integrated in time under the influence of static magnetic field turbulence, which is given as a superposition of parallel, circularly polarized Alfvén waves with equal propagation velocities (slab model). In this model, the ion energy in the wave rest frame is constant, thus there is no energy diffusion of ions. Both right- and left-hand polarized waves are included. Although each mode is non-compressional, superposition of the waves yields a ponderomotive compressional field, which may act to mirror-reflect the ions. In the simulation, we assume a power-law distribution of wave power with a spectral index γ when $k_{min} < k < k_{max}$, and zero otherwise, where k, k_{min}, k_{max} are respectively the wave number, the minimum, and the maximum wave numbers included in the simulation. The wave phases are assumed to be random.

Figure 2 shows the time evolution of the distribution of ion pitch angle cosine, μ. For each panel, the horizon-

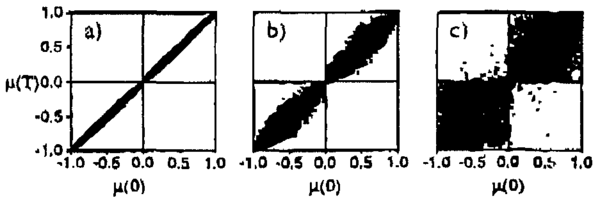

FIGURE 2. Time evolution of the particle pitch angle distribution.

tal axis represents the initial distribution, $\mu(0)$, and the vertical axis denotes the distribution at some later times, $\mu(T)$, with (a) $T = 40$, (b) $T = 640$ and (c) $T = 10240$. Each dot represents a single test particle. Parameters used are: the ion velocity, $v = 10$, $\gamma = 1.5$, $k_{min} = 6.13 \times 10^{-3}$, $k_{max} = 3.14$ and the variance of the normalized perpendicular magnetic field fluctuations, $\langle B_{perp}^2 \rangle = 4 \times 10^{-4}$.

At $T = 40$, the distribution of μ has not much evolved, and so the dots are almost aligned along the diagonal line in panel (a). Later, at $T = 640$, pitch angle diffusion is more evident, represented by thickening of the diagonal line (panel (b)). It is also clear that the diffusion is absent in essentially two regimes, $\mu \approx 0$ and $|\mu| \approx 1$. The former is due to the lack of waves which resonate with near 90° pitch angle ions. And the latter is due to geometry (i.e., the Jacobian), which appears as the pitch angle is transformed to its cosine, vanishes at $|\mu| = 1$, representing that a small deviation of the pitch angle from an exactly parallel direction does not give rise to a deviation of μ of the same order.

Clearly, the majority of the ions stay within the hemisphere in which they began. However, we should also note that a few ions did escape into the opposite hemisphere (see also (22)). More detailed analysis on test particle simulations will be done in a future study.

FINAL COMMENTS

What is the physical process of scattering particles across 90° pitch angle? The presence of large amplitude waves with $\delta B/B_0 \approx 1$ could lead to large, single-encounter pitch angle scattering across 90° (see (23)). This is a nonresonant interaction which involves large amplitude waves and is not included in the present quasi-linear theories. A second process is particle mirroring via interaction with $|\mathbf{B}|$ variations (24, 25, 26).

Random superposition of small amplitude waves may produce the $|\mathbf{B}|$ power spectra shown in Figure 2, and lead to mirroring across 90°. Computer simulations using particle-in-cell (PIC) codes should be useful to determine the relative effectiveness of the above two processes. Analytical expressions could then be derived which could be used to modify the Fokker-Plank transport coefficients.

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